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GEOLOGY AND NATURAL GAS PRODUCTION OF THE LOWER SILURIAN MEDINA GROUP AND EQUIVALENT ROCK UNITS IN PENNSYLVANIA

Robert G. Piotrowski

**COMMONWEALTH OF PENNSYLVANIA
DEPARTMENT OF ENVIRONMENTAL RESOURCES
OFFICE OF RESOURCES MANAGEMENT
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by Robert G. Piotrowski

Marathon Oil Company

(formerly Pennsylvania Geological Survey)

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by

Robert G. Piotrowski¹

ABSTRACT

The Lower Silurian clastics are important natural gas bearing units in Pennsylvania. Natural gas production is known from the Lower Silurian Tuscarora Formation of central Pennsylvania and the Lower Silurian Medina Group sandstones of northwestern Pennsylvania. Natural gas in the Tuscarora is found in structurally controlled fracture-porosity traps. The wells have had high initial volumes, but the gas has had low Btu heating values. The Medina Group of northwestern Pennsylvania is the most actively explored Lower Silurian unit in the state, and several producing fields exist in northwestern Pennsylvania. The Medina Group will also be the primary target for drilling in the Pennsylvania portion of Lake Erie. The trap type is primarily stratigraphic; production depends upon the amount of porosity and permeability in the sandstone.

The Lower Silurian clastics were deposited westward into central and northwestern Pennsylvania from eastern highlands raised during the Late Ordovician to Silurian Taconic orogeny. The sequence can be divided into three major facies: (1) the eastern Pennsylvania Shawangunk Formation, (2) the central Pennsylvania Tuscarora Formation, and (3) the northwestern Pennsylvania Medina Group. The Medina Group is further subdivided for mapping into the Whirlpool Sandstone, the Cabot Head Shale, and the Grimsby sandstone tongue.

Regional stratigraphic cross sections, isopach maps, and facies maps were constructed for the Medina Group in northwestern Pennsylvania in order to understand the regional geology. The Medina is interpreted as a large delta complex deposited in northwestern Pennsylvania during Lower Silurian time. The ancient shoreline is defined along a line from central Warren County to northern Beaver County. Sediment was deposited in northwestern Pennsylvania through a major distributary system through Butler County. The Medina delta system is channel dominated near the shoreline and bar dominated toward the northwest in Erie County and northwestern Crawford County. Natural gas production from the Medina Group is mostly stratigraphically controlled by the amount of primary porosity and permeability in the sandstones. Structure is not a major con-

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trolling factor, although fracture-controlled porosity exists in some areas. The sandstones northwest of the shoreline in both the bar- and channel-dominated delta systems have reservoir potential.

The regional depositional framework of the Lower Silurian in Pennsylvania indicates that the Shawangunk Formation of eastern Pennsylvania is a near-source depocenter. Another such depocenter is located in Virginia. These two accumulation centers merge to form a large detrital apron thinning to the northwest. This detrital apron in Pennsylvania is the Tuscarora Formation, which is interpreted as a continental fluvial deposit. The terrestrial Tuscarora is replaced in northwestern Pennsylvania by the Medina Group. The Medina Group is primarily a complex system of small deltas. The modern Mississippi Delta is a good analog. Both the bar-dominated and channel-dominated deltaic environments of the Medina provide excellent potential for the development of reservoir sandstones. Development drilling of these sandstones is expected to continue. The Tuscarora Formation of central Pennsylvania has potential as a higher risk exploratory drilling target.

INTRODUCTION

The Lower Silurian clastics are important natural gas bearing units in Pennsylvania. This clastic sequence was deposited westward into central and northwestern Pennsylvania from eastern highlands raised during the Late Ordovician to Silurian Taconic orogeny. The sequence is composed of three units: (1) the eastern Pennsylvania Shawangunk Formation, (2) the central Pennsylvania Tuscarora Formation, and (3) the northwestern Pennsylvania Medina Group. General areas of natural gas production from these Lower Silurian clastics are indicated in Figure 1. Production is primarily in northwestern Pennsylvania in Erie, Crawford, Warren, Venango, and Mercer Counties; two areas of production occur in central Pennsylvania in Fayette and Centre Counties.

Gas production from the Lower Silurian in central Pennsylvania is limited to the Heyn pool, Summit field, in Fayette County and the Devils Elbow field in Centre County. The Heyn pool was discovered in 1964 by the #1 Leo Heyn well, drilled to a total depth of 11,566 feet. The well produced 40,000 Mcf from Tuscarora sandstone in three months before being abandoned due to mechanical problems (Lytle and others, 1965). The Devils Elbow field was discovered in 1977 by the #1 Texasgulf well, drilled to a total depth of 11,187 feet. The well had an initial potential of 20,000 to 37,000 Mcf natural open flow per day from the Tuscarora (Heyman and Cozart, 1978; Piotrowski and others, 1979). This field is currently being developed. Both the Heyn pool and Devils Elbow field are structurally controlled fracture-porosity traps in the Lower Silurian Tuscarora sandstone and both

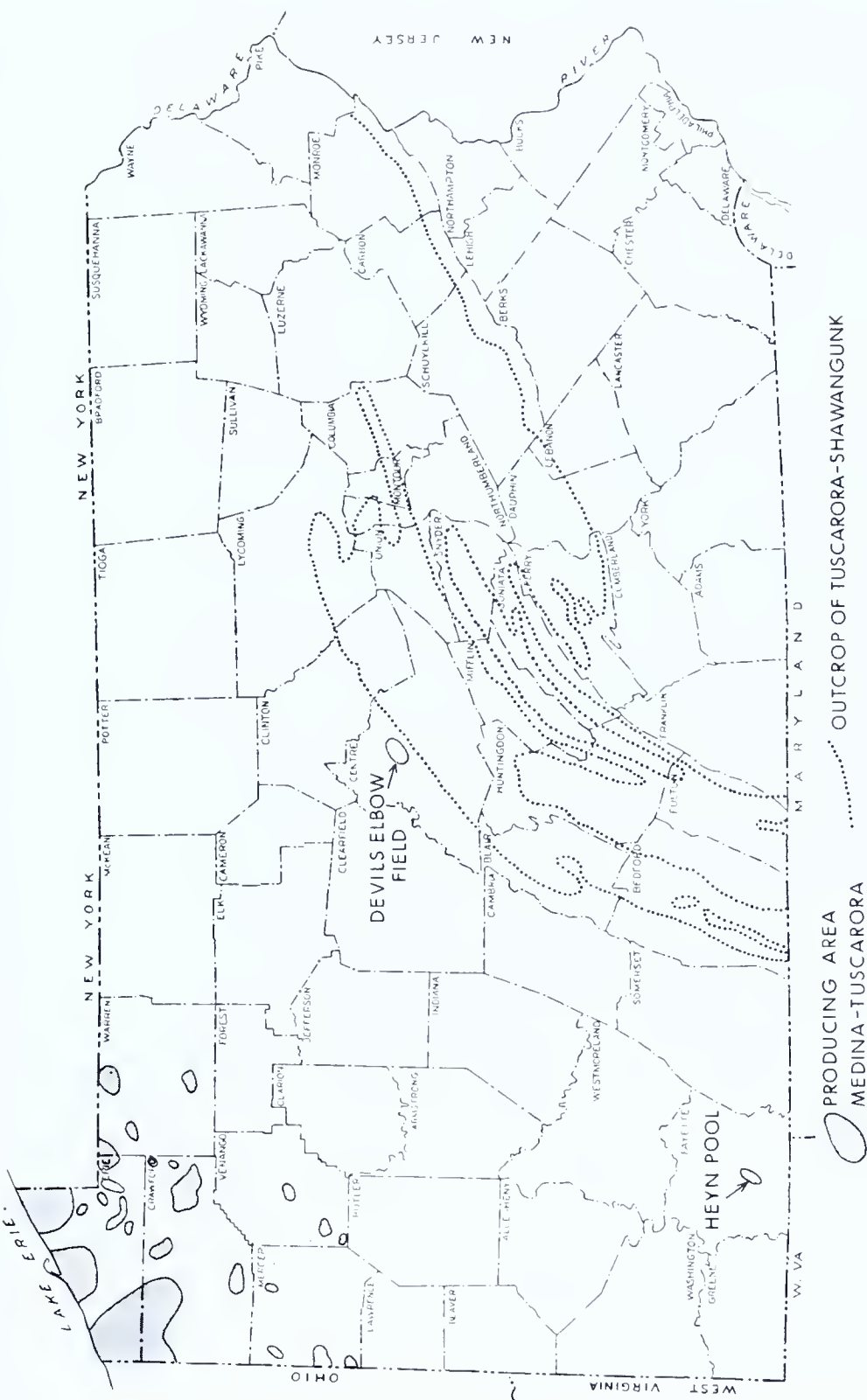


Figure 1. Gas production from the Medina Group and Tuscarora Formation in Pennsylvania.

have gas that has a high nitrogen content and heating values of 850 to 880 Btu per cubic foot, which is below pipeline quality (1,000 Btu per cubic foot). This is typical of Tuscarora wells in northern West Virginia (Patchen, 1968).

Gas production in northwestern Pennsylvania is from the Lower Silurian Medina Group and is shown in general in Figure 1, and in more detail on Plate 1. Drilling for Lower Silurian sandstone reservoirs has increased substantially from 1977 to the present, and there is activity in several counties. This is a direct result of increases in natural gas prices since 1977, and the activity is expected to continue. The Medina Group will also be the primary target zone for drilling in the Pennsylvania portion of Lake Erie, which may soon be opened for exploration. The trap type in the Medina Group is primarily stratigraphic, and commercial hydrocarbon production is controlled by the amount of porosity and permeability found in deltaic sandstones (Kelley and McGlade, 1969).

The objectives of this study are to stratigraphically correlate all Lower Silurian clastic facies in Pennsylvania, to map the definable units, and to understand the regional depositional framework. The study will emphasize the Medina Group in northwestern Pennsylvania because most drilling activity has occurred there, and it is the area where most subsurface data are available.

GENERAL STRATIGRAPHY

The Lower Silurian clastics have been the subject of much study, and a wide range of both formal and informal terminology exists. Figure 2 (see centerfold) shows a synthesis of terms used in various states by various workers. The preferred usage depends upon the tradition in the area of study and the method of study used. Surface mappers prefer a different classification than subsurface workers. Subsurface workers differ depending upon whether samples or mechanical logs were the primary tools used. The terminology used in this project (Figure 2) divides the Lower Silurian clastics into three primary facies types: (1) the eastern Pennsylvania Shawangunk Formation, (2) the central Pennsylvania Tuscarora Formation, and (3) the northwestern Pennsylvania Medina Group.

SHAWANGUNK FORMATION

The term Shawangunk was first used by Mather (1840). It is generally described as a mostly coarse, well-indurated quartz sandstone and conglomerate having rounded to angular pebbles. Shales are irregular, thin, and never abundant. The maximum thickness of the Lower Silurian clastic sequence is at the Delaware Water Gap, where over 1,600 feet of the Shawangunk Formation is exposed (Smith, 1970). The contact of the Shawangunk

with the underlying Martinsburg Formation is an angular unconformity. The boundary between the Shawangunk and the overlying Bloomsburg Formation is transitional (Epstein and Epstein, 1972). The Shawangunk has yielded a sparse eurypterid and fish fauna and in some places the trace fossil *Arthropycus* (Yeakel, 1962). The lower Shawangunk is equivalent to the Tuscarora Formation of central Pennsylvania, and the upper Shawangunk replaces the marine shales of the Clinton Group. The Green Pond Conglomerate of New Jersey is a possible isolated remnant (Smith, 1970). The distribution of the Shawangunk in Pennsylvania is indicated in Figure 3. The change from Shawangunk to Tuscarora along the outcrop belt is taken from the state geologic map (Gray and others, 1960). The distribution in the subsurface is based upon three deep wells, one in Luzerne County, one in Wayne County, and one in Pike County.

TUSCARORA FORMATION

The Tuscarora was named by Darton (1896) from the Tuscarora Mountains of Pennsylvania. In general, it is a white to light-gray, fine- to coarse-grained sandstone having conglomeratic zones. Quartz grains are rounded and well sorted. The sandstone is well cemented with secondary quartz. It is this property that causes the Tuscarora to commonly break through quartz grains, and it is often described as a sedimentary quartzite (Folk, 1960). The formation thins from southeast to northwest (Yeakel, 1962). The boundary between the Tuscarora and the underlying Juniata Formation in central Pennsylvania is a gradational one usually picked on color change from gray Tuscarora to red Juniata. This transition zone is indicated on the stratigraphic chart (Figure 2) as the Juniata-Tuscarora Formation. The Tuscarora rests on the Martinsburg Formation; an angular unconformity is present east of Harrisburg. The top of the Tuscarora is a gradational change to the shale of the overlying Rose Hill Formation. The Castanea is a member of the generally gray to white Tuscarora. The Castanea is predominantly red and embraces more interbeds of siltstone and shale among the beds of sandstone than does the underlying Tuscarora. The overlying Rose Hill Formation contains a transitional basal, iron-rich (reddish), sandy section which is difficult to differentiate from the underlying Castanea Member where present (Cate, 1965). The Cresaptown is one of the basal sandstones in the Rose Hill in south-central Pennsylvania and is an excellent stratigraphic marker. The Tuscarora is unfossiliferous except for the common trace fossil *Arthropycus* and some vertical tubes referred to as *Scolithus* (Yeakel, 1962). The Tuscarora is equivalent to the Lower Silurian Medina Group of northwestern Pennsylvania.

MEDINA GROUP

The Medina Group was first named by Vanuxem (1840) in New York. The Medina Group in Pennsylvania is composed of the basal Whirlpool

Sandstone, the Manitoulin Dolomite, the Cabot Head Shale, and the Grimsby sandstone tongue. The Whirlpool Sandstone is generally a light-gray quartzose sandstone to siltstone. It is a consistently thin unit in northwestern Pennsylvania, ranging generally from 10 to 25 feet in thickness. The Whirlpool lies disconformably on the Ordovician Queenston Shale in northwestern Pennsylvania (Cate, 1965), and is truncated by an apparent unconformity in central Warren, Forest, Clarion, Armstrong, Butler, and Beaver Counties. This truncation marks the change from the Medina Group in northwestern Pennsylvania to the Tuscarora (Figures 3 and 4). The upper boundary is gradational to the Cabot Head Shale or the thin Manitoulin Dolomite.

The Manitoulin is an argillaceous brown dolomite which is identified on the Canadian side of Lake Erie (Figure 4) and is probably present as a thin unit in the Pennsylvania portion of the lake. The Cabot Head Shale is a dark-green to black shale, apparently of marine origin (Knight, 1969). It contains thin, lenticular, quartzose siltstone laminations, which increase toward its gradational upper boundary. The Cabot Head Shale is thickest in western Erie, Crawford, and Mercer Counties and thins toward the east-southeast. The Cabot Head Shale is truncated by an unconformity at approximately the same location as the underlying Whirlpool (Figures 4 and 5). In outcrop in Ontario, Canada, the Cabot Head is fossiliferous and contains an open-marine fauna (Martini, 1971).

The Grimsby sandstone tongue overlies the Cabot Head Shale, and the boundary is gradational. The Grimsby sandstone tongue is made up of fine to very fine, light-gray to red sandstones and siltstones. It contains thin, discontinuous beds of red and dark-gray, silty shale. The grains are subrounded to subangular. The cementing materials are silica and hematite along with a small amount of calcite and clay material. Hematite produces the red color and is the principal cementing material where silica is absent or present in a limited amount (Knight, 1969). The red color is generally restricted to the central portion of the Grimsby and is bounded, top and bottom, by light-gray to white sandstones. This color differentiation can only be seen in a small portion of Pennsylvania. It is this color differentiation that has been used by some workers to define subdivisions within the Grimsby sandstone tongue. The gray to white sandstones are called by various names: Stray Clinton, White Clinton, Thorold, Power Glen, and Tracy (Figure 2). The red sandstones are called Grimsby or Red Clinton. Commercial hydrocarbons in the Medina Group are controlled by the presence of porosity and permeability in the sandstone lenses and are not dependent upon color. In some areas commercially significant porosity and permeability are restricted to the central red hematite-cemented sandstones, but there are many areas where commercially significant porosity and permeability are present in the gray or white sandstone beds. Thus the entire genetically related sandstone bundle, bounded by the overlying Reynales Dolomite and

underlying Cabot Head Shale, is treated as a single mapping unit in this study and informally referred to as the Grimsby sandstone tongue. This is similar to the usage of Knight in Ohio (Knight, 1969). The Grimsby tongue is thickest in the southeast and thins across Lake Erie into Canada. The Grimsby sandstones are fossiliferous in Ontario, Canada, and western New York and contain a normal marine fauna. In central New York the fauna is transitional (Martini, 1971).

CORRELATIONS

The framework for this study is set by a series of regional stratigraphic cross sections. Figure 3 shows the locations of these sections. The purposes of the cross sections are to define the regional mapping units and to indicate the equivalency of these units to units in Ohio and New York and across Lake Erie into Canada. The cross sections also tie the Lower Silurian Medina Group sandstones of northwestern Pennsylvania to the equivalent Lower Silurian Tuscarora Formation in central Pennsylvania. Two of the cross sections are schematically illustrated in Figures 4 and 5. All nine detailed work sections (Figure 3) are available on open file at the Oil and Gas Geology Division of the Pennsylvania Geological Survey, 1201 Kossman Building, 100 Forbes Avenue, Pittsburgh, Pennsylvania 15222.

Cross section F-E3 extends from Ontario, Canada, across Lake Erie into Pennsylvania and then across the northern counties of Pennsylvania (Figures 3 and 4). Cross section A2-E2 extends from the city of Erie to south-central Pennsylvania in Bedford County near the outcrop of the Tuscarora sandstone. Both of the schematic cross sections illustrate the regional mapping units in the Lower Silurian in northwestern Pennsylvania. This includes the Queenston Shale and Clinton Group, which bound the Lower Silurian Medina Group sandstones. The Medina Group is further subdivided into the basal Whirlpool Sandstone, the Cabot Head Shale (sometimes including a thin dolomite, the Manitoulin, which is present in Canada and portions of Lake Erie), and the Grimsby sandstone tongue. The equivalency of the Medina Group to the Tuscarora Formation of central Pennsylvania is also illustrated. The cross sections are based primarily on gamma-ray logs having some sample control. The 50 percent clean sand cutoff is also illustrated on each log. The method used to determine this cutoff follows that of Knight (1969). The total amount of sandstone is highest in the southeast and decreases toward the northwest. The sandstones are also stratigraphically lower in the section in the southeast and climb stratigraphically in the section toward Lake Erie. Both the Grimsby sandstone tongue and the Whirlpool Sandstone are present below the Pennsylvania portion of Lake Erie. The Cabot Head Shale is thickest in the northwest and thins toward the southeast. The Whirlpool Sandstone is very uniform in thickness

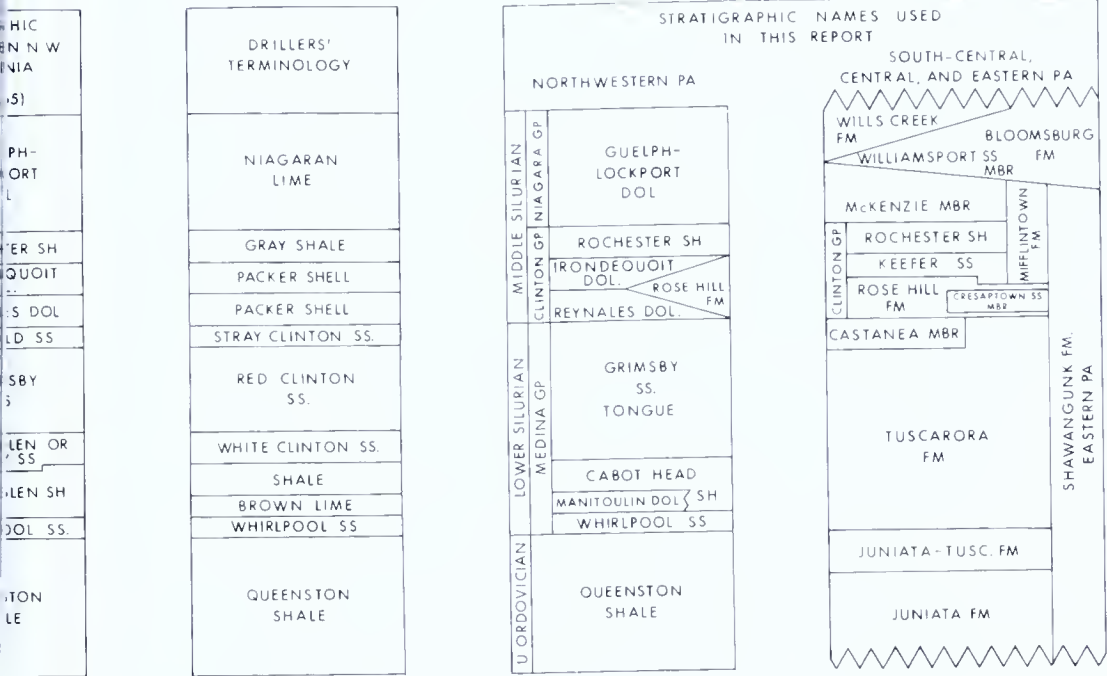
STRATIGRAPHIC NAMES USED IN SOUTHERN ONTARIO, CANADA (Beards, 1967)		
MIDDLE SILURIAN	NIAGARA GP	GUELPH- LOCKPORT DOL
	CLINTON GP	DeCEW DOL MBR ROCHESTER SH
		IRONDEQUOIT DOL
		REYNALES DOL NEAHGA SH THOROLD SS
	LOWER SILURIAN CATARACT GP	GRIMSBY SS CABOT HEAD SH MANITOULIN DOL WHIRLPOOL SS
	U. ORDOVICIAN	QUEENSTON SHALE

STRATIGRAPHIC NAMES USED IN WESTERN NEW YORK (Fisher, 1954)		
MIDDLE SILURIAN	NIAGARA GP	GUELPH- LOCKPORT DOL
	CLINTON GP	DeCEW DOL MBR ROCHESTER SH
		IRONDEQUOIT DOL
		REYNALES DOL NEAHGA SH THOROLD SS
	LOWER SILURIAN MEDINA GP	GRIMSBY SS CABOT HEAD SH MANITOULIN DOL WHIRLPOOL SS
	U. ORDOVICIAN	QUEENSTON SHALE

STRATIGRAPHIC NAMES USED IN OHIO (Knight, 1969)		
MIDDLE SILURIAN	NIAGARA GP	LOCKPORT DOL CLINTON FM BRASSFIELD LS THOROLD SS
	LOWER SILURIAN ALBION GP CATARACT FM	GRIMSBY SS CABOT HEAD SS CABOT HEAD SH MANITOULIN DOL WHIRLPOOL SS
	U. ORDOVICIAN	QUEENSTON SHALE

STRATIGRAPHIC NAMES USED IN PENNSYLVANIA (Cate, 1959)		
MIDDLE SILURIAN	NIAGARA GP	LOCKPORT DOL ROCHESTER SH IRONDEQUOIT DOL REYNALES DOL THOROLD SS
	LOWER SILURIAN MEDINA GP	GRIMSBY SS CABOT HEAD SS CABOT HEAD SH MANITOULIN DOL WHIRLPOOL SS
	U. ORDOVICIAN	QUEENSTON SHALE

Figure 2. Correlation of Middle and Lower Silurian



Stratigraphic units in Pennsylvania and related areas.

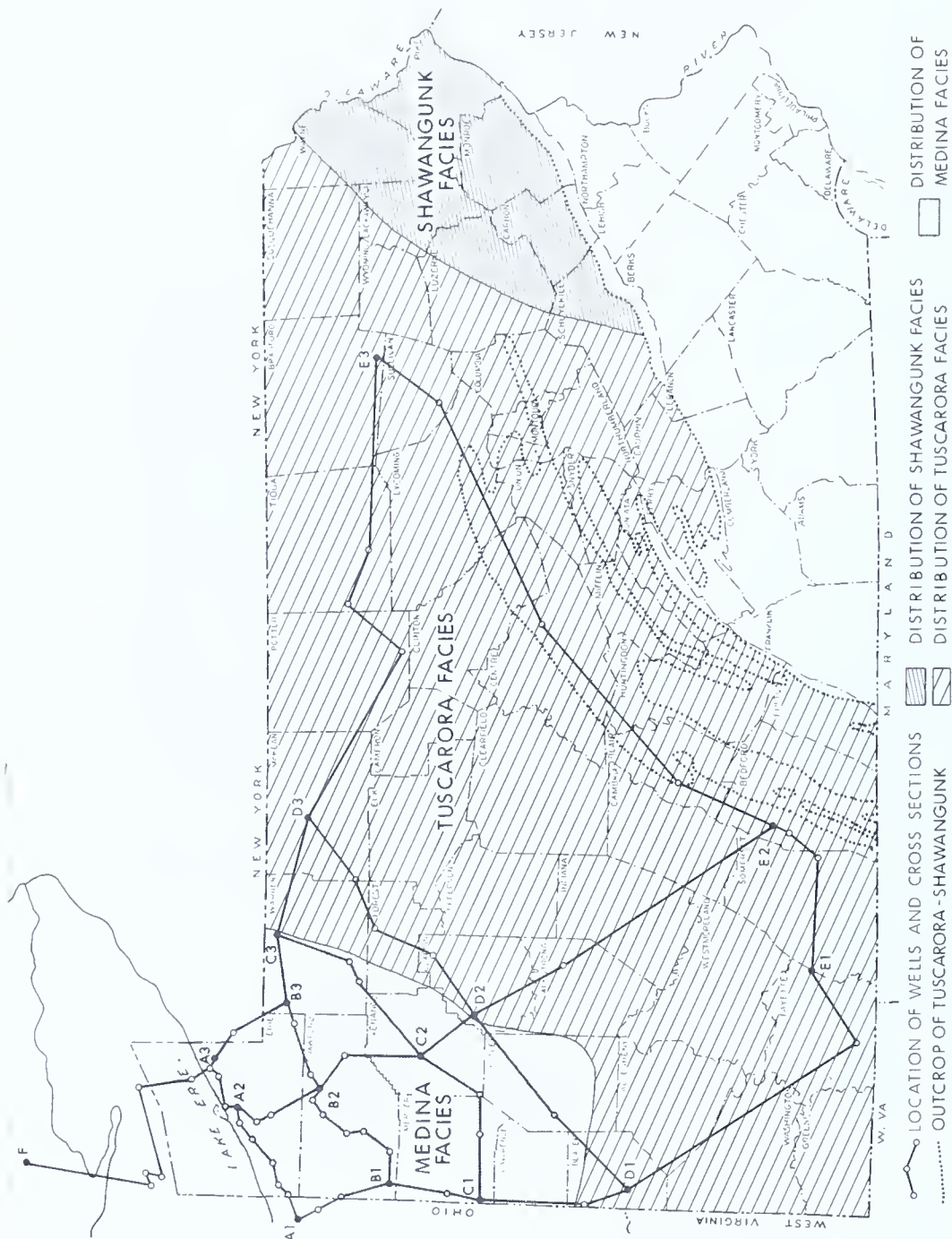


Figure 3. Index map showing lines of regional stratigraphic cross sections and distribution of Medina and equivalent facies.

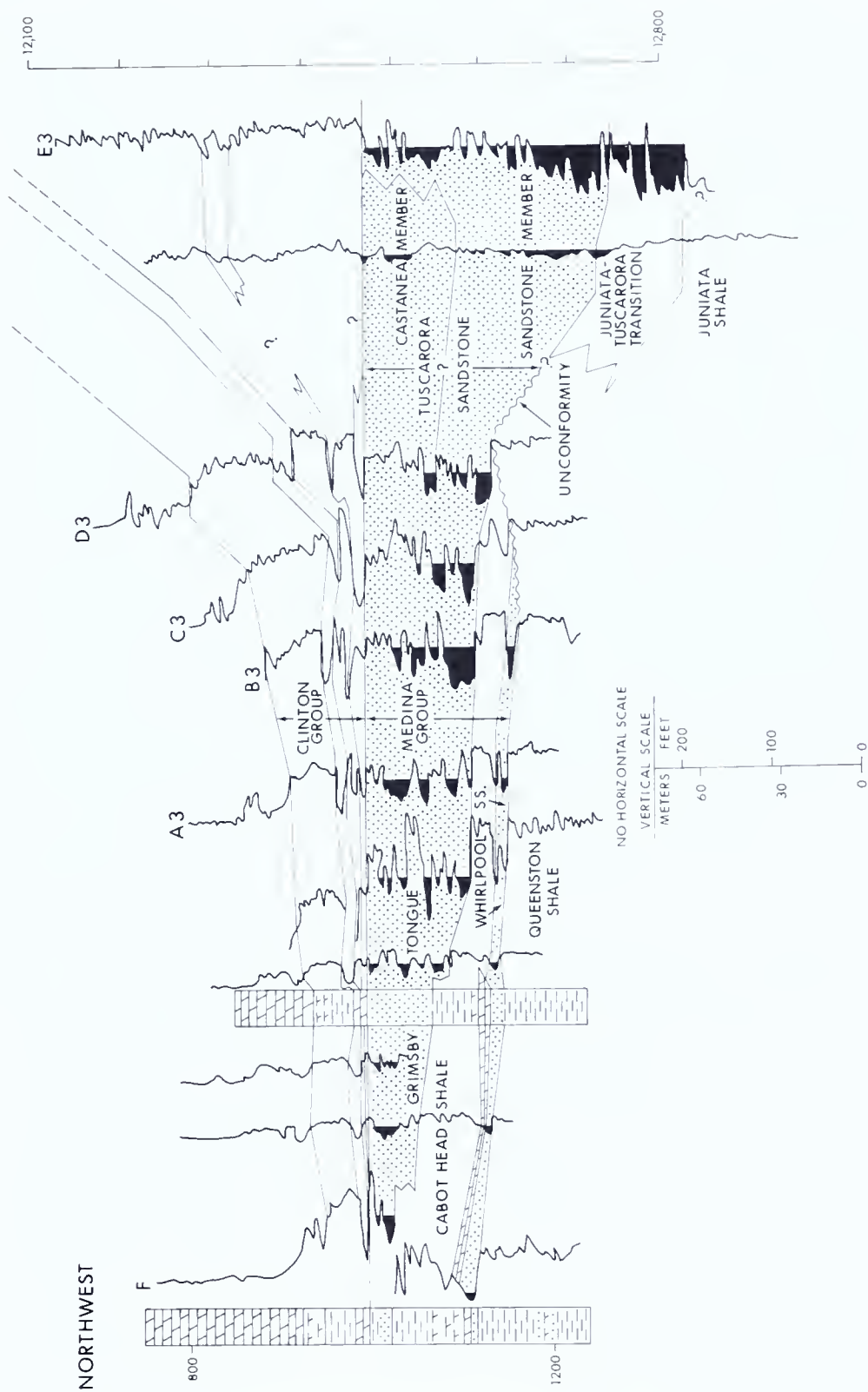


Figure 4. Stratigraphic cross section F-E3, in the Lower Silurian Medina Group.

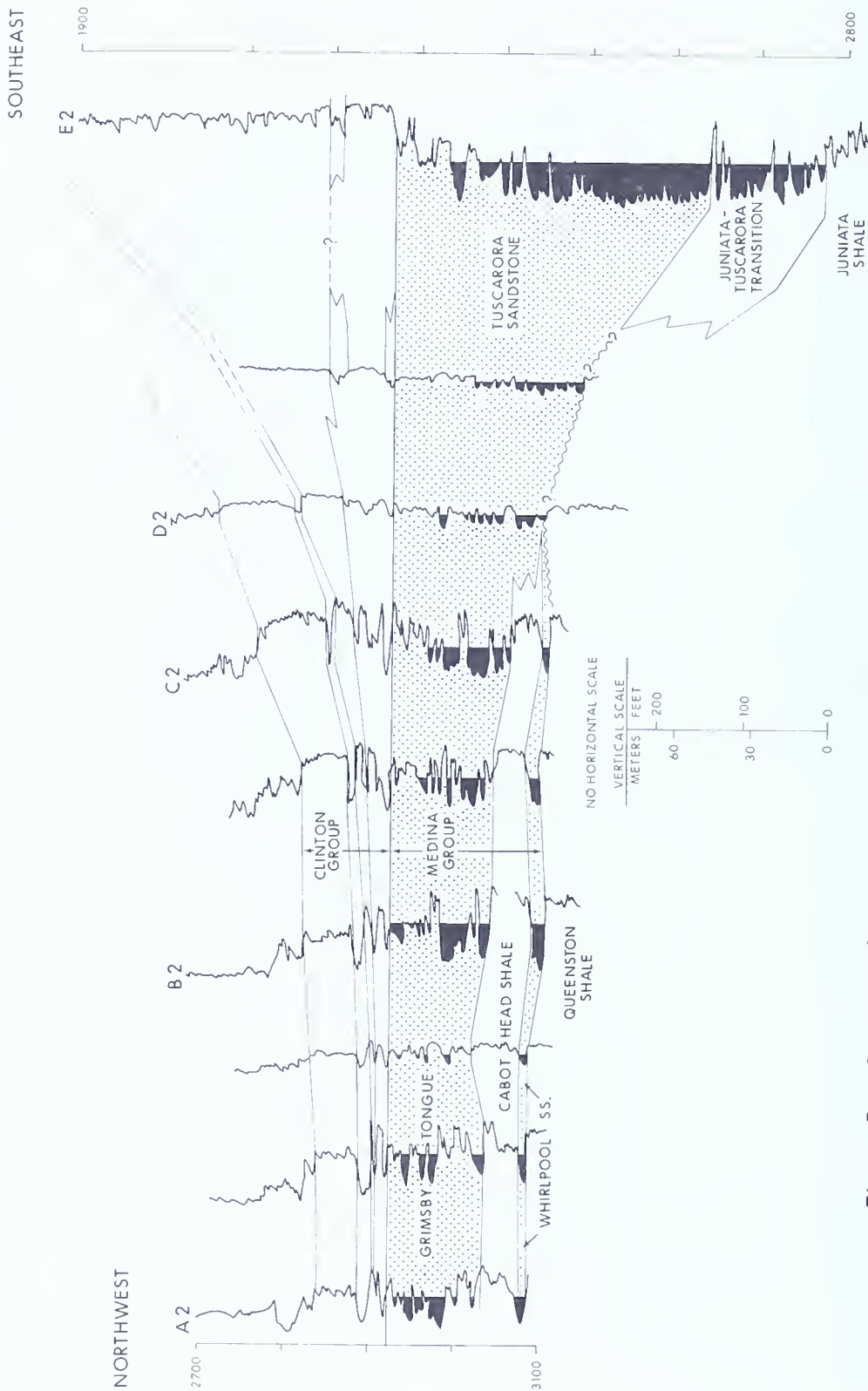


Figure 5. Stratigraphic cross section A2-E2 in the Lower Silurian Medina Group.

and correlative over a large part of northwestern Pennsylvania. An apparent unconformity, which cuts out the Whirlpool Sandstone and Cabot Head Shale, is also observed on both cross sections. This termination of the Whirlpool Sandstone and Cabot Head Shale is where the boundary between the Medina Group and the Tuscarora Formation is placed. Log calculations also indicate that this boundary is an apparent porosity boundary, whereas southeast in the Tuscarora little primary porosity remains due to silica cementation, and generally does not exceed 3 percent. In the Medina Group, northwest of the boundary, porosity of 6 to 9 percent is common.

The cross-sectional geometry of the Medina Group is very similar to that described by Fisk (1961) for the modern Mississippi Delta. This analogy was also used by Knight (1969) for the Medina Group (Clinton of Ohio usage) in Ohio. The Whirlpool is a thin, widespread, strand-plain sand deposited during the initial stage of a marine transgression. The Cabot Head is a marine prodelta shale deposited as the marine transgression proceeded. It is this dark-green to black marine shale that is the probable source of the hydrocarbons found in the Medina Group. The overlying Grimsby sandstone tongue consists of deltaic bar-finger and channel sandstones prograding from southeast to northwest. The termination of the Whirlpool Sandstone and Cabot Head Shale is interpreted as the ancient shoreline at the time of Medina deposition into northwestern Pennsylvania. The massive sandstones at the base of the Grimsby tongue are river-dominated channel sandstone, whereas the sandstones stratigraphically higher near Lake Erie are more marine dominated.

MAPS

NATURAL GAS PRODUCTION FROM MEDINA GROUP SANDSTONES, AND DRILLING DEPTH TO THE TOP OF THE QUEENSTON SHALE

A series of eleven maps were constructed detailing the Medina Group in northwestern Pennsylvania. Two of the maps, gas production (Plate 1) and drilling depth (Plate 2), are of a general descriptive nature. The detailed gas production map was discussed previously. The drilling depth map illustrates a contoured drilling depth from ground surface to the top of the Upper Ordovician Queenston Shale. This map indicates that the base of the Medina Group is shallowest in Lake Erie (1,500 feet deep) and increases in depth to the southeast, where, in central Armstrong County, it is 9,500 feet deep. Most active Medina development drilling is at 5,000 feet or shallower depths.

STRUCTURE ON TOP OF THE QUEENSTON SHALE

One structure-contour map, on top of the Queenston Shale, is included in the map series (Plate 3). This map indicates rather uniform dip to the south-east and shows subsea elevations ranging from -1,000 feet in Lake Erie to -7,000 feet in Armstrong County. Some minor nosing is observed in areas where well control is good. It is inferred from the map that natural gas production from the Medina is not obviously structurally controlled and, therefore, must be primarily stratigraphically controlled. Fracture-controlled porosity in certain areas is probably the major structural influence in the production of Medina gas. Stratigraphic control of production is recognized in two detailed field studies on the Medina in Pennsylvania, the Pierce pool study in Erie County (Kelley and McGlade, 1969) and the Kastle pool study in Crawford County (Kelley, 1966). The only structural closure on the map is in eastern Mercer County near the Venango County line. This structure is called the Henderson dome and was first recognized as a unique feature in northwestern Pennsylvania by Fettke (1950). The dome is roughly circular and has a structural closure of 150 feet on the Venango First sand of the Upper Devonian. The lower part of the Clinton Group, the entire Medina Group, and the Queenston red shales are missing over the dome and their places are taken by fractured gray shale of Upper Ordovician Reedsville lithology. The section from the source to the Middle Silurian Lockport Dolomite is normal. Fettke interpreted this feature as a diapiric intrusion of Reedsville shale which pushed aside the Medina Group sandstones and the Queenston red shales. An anomalously thick Medina sandstone section, which is gas productive, is encountered off the southeast flank of the dome. This thick sandstone section could be the result of slumping off the dome, faulting, or depositional thickening near an active tectonic feature. Further drilling and study of this unique feature are necessary.

ISOPACH MAP OF THE MEDINA GROUP

A series of isopach maps has also been constructed to show the regional distribution of the Lower Silurian units in northwestern Pennsylvania. This includes isopachs of the Clinton Group and Medina Group and also isopachs of the Whirlpool Sandstone, Cabot Head Shale, and Grimsby sandstone tongue of the Medina Group.

The isopach map of the total Medina Group is shown on Plate 4. The thickest area of Medina deposition occurs in Butler County, where the Medina Group is in excess of 200 feet. The maximum thickness of the Medina Group is off the southeastern flank of the anomalous Henderson dome. No Medina is present on the crest of the dome. Two thin areas of Medina are present in eastern Warren County and western McKean County and also in northern Beaver County, just north of the West Virginia panhandle. These thin areas correspond to the areas where the Whirlpool Sandstone

and Cabot Head Shale are truncated by an unconformity (see schematic cross sections, Figures 4 and 5). This is the interpreted shoreline during Medina deposition; the main river input system was feeding from Butler County into northwestern Pennsylvania. Except for the anomalous Henderson dome, the geometry of the Medina is lobate and the unit thins toward the north-northwest. The Medina Group appears to be a channel-dominated deltaic deposit in the southeast, its thicknesses striking normal to the proposed shoreline. Near Lake Erie the geometry changes, the thicknesses becoming parallel to the proposed shoreline and indicating a more marine dominated deltaic environment.

ISOPACH MAP OF THE CLINTON GROUP

The isopach map of the overlying Clinton Group (Plate 5) is significantly different from that of the Medina Group. The Clinton is thinnest in Lake Erie, approximately 80 feet, and thickens toward the southeast to approximately 300 feet. The Clinton is present on the Henderson dome but it is thin on the crest. The rate of change of the Clinton Group may be significant. Northwest of the proposed shoreline, which runs from central Warren County to northern Butler County, the contours are relatively widely spaced, indicating stability and slow deposition. Southeast of the line, the Clinton Group thickens rapidly. Calculations of porosity in the Silurian sandstones from density logs indicate that sandstones southeast of this line are generally tight, having porosities of 3 percent or less. Northwest of this line, porosities in the sandstones are generally better, 6 to 9 percent being common. One factor in the destruction of primary porosity by silica cementation may be the rapid subsidence of the area southeast of this line as evidenced by the rapid thickening of the Clinton shales.

ISOPACH MAP OF THE WHIRLPOOL SANDSTONE

The distribution of the Whirlpool Sandstone of the Medina Group is illustrated on Plate 6. The Whirlpool is surprisingly uniform, ranging from 10 to 20 feet thick over the entire northwestern corner of Pennsylvania. The Whirlpool is missing along a line from central Warren to northern Butler County. This truncation is interpreted as the shoreline during Medina deposition. The Whirlpool is also missing on the anomalous Henderson dome. The uniform blanket deposition of this sand over such a large area supports the interpretation of a strand-plain sandstone similar to what is seen in the modern Mississippi Delta (Fisk, 1961).

ISOPACH MAP OF THE CABOT HEAD SHALE

The distribution of the Cabot Head Shale (Plate 7) indicates that the shale is thickest, greater than 80 feet, in the northwest along the Ohio border, and

thins to the southeast. Along the proposed shoreline it is truncated by an unconformity. The unit is also missing on the crest of the Henderson dome. The geometry of this shale fits that of a marine prodelta shale similar to that of the modern Mississippi Delta (Fisk, 1961).

ISOPACH MAP OF THE GRIMSBY SANDSTONE TONGUE

The isopach map of the Grimsby sandstone tongue (Plate 8) is very similar to that of the total Medina Group. The thickest area in northwestern Pennsylvania is in Butler County, which was the apparent sediment-input center into northwestern Pennsylvania during Medina time. The Grimsby is relatively thin along a line from central Warren to northern Butler County, the interpreted shoreline. The geometry of the Grimsby in northwestern Pennsylvania is lobate normal to the proposed shoreline and becomes parallel to the shoreline near Lake Erie. The Grimsby is missing over the Henderson dome and is abnormally thick off the southeastern flank. The geometry of the Grimsby is that of a prograding deltaic depositional system.

Because the Medina Group is the primary target zone for natural gas production in northwestern Pennsylvania, two types of facies maps were constructed for the group. These are a sand/shale ratio map and two sandstone quality maps.

SAND/SHALE RATIO IN THE MEDINA GROUP

The sand/shale ratio map (Plate 9) is based upon the 50 percent gamma-ray-log deflections (Knight, 1969). The map indicates depositional trends, source direction, and most importantly the interrelationship between reservoir rocks and source rocks. The depositional trends indicated are identical to those shown on the isopach maps of the Medina Group and the Grimsby sandstone tongue. The source of the sandstone was toward the southeast, and there was a major sediment input center through Butler County. The sandstones were deposited in a deltaic environment which was channel dominated toward the southeast and more bar dominated toward the northwest near Lake Erie. The total amount of source rock decreases toward the southeast as the sand content of the Medina increases. Medina natural gas production is known in Pennsylvania in areas having sand/shale ratios of less than one. Thus, sufficient source rock for commercial production in the Medina Group should exist in most of northwestern Pennsylvania.

NET SAND (50 AND 75 PERCENT CUTOFFS) IN THE MEDINA GROUP

Two sandstone isolith maps are also illustrated on Plates 10 and 11. One is based on a 50 percent gamma-ray sandstone deflection, and the other on a

75 percent gamma-ray sandstone deflection. Both maps are sandstone quality maps and indicate potential producing sandstone (net feet of potential reservoir) within the Medina Group. Both maps have very similar geometries and are also similar to the Medina Group isopach map. The amount of sandstone is greater to the southeast and decreases toward the northwest. Along the proposed shoreline, 80 to 100 feet of sandstone (50 percent gamma-ray deflection) is observed. The amount of sandstone decreases directly east of the shoreline in McKean and Warren Counties. Northwest of the proposed shoreline, sandstone decreases toward Lake Erie. A definite channel geometry, normal to shoreline, changes to a bar geometry, parallel to shoreline, near Lake Erie. The amount of potential reservoir ranges from 80 feet (50 percent gamma-ray deflection) near the shoreline to 20 to 30 feet (50 percent gamma-ray deflection) in Lake Erie. The Henderson dome has no sandstone on the crest and over 200 feet off the southeastern flank.

DEPOSITIONAL FRAMEWORK OF THE MEDINA GROUP IN NORTHWESTERN PENNSYLVANIA

Detailed mapping of the Medina Group sandstones in northwestern Pennsylvania shows a deltaic system of deposition in Lower Silurian time. The shoreline is defined by the truncation of the strand-plain Whirlpool Sandstone and the marine Cabot Head Shale. The shoreline is also defined by thin areas illustrated on the isopach map of the Medina Group. The area of sediment input into northwestern Pennsylvania is in Butler County, where the total Medina section is thick and total sand content is relatively high. The geometry of the sandstone bodies indicates that the depositional system is channel dominated near the shoreline and is more bar dominated toward the northwest in Erie and northwestern Crawford County. Total potential reservoir sandstone is highest near the shoreline and decreases toward the northwest. The sand/shale ratio map indicates sufficient source rock for hydrocarbon production northwest of the shoreline.

Natural gas production in the Medina Group is controlled by stratigraphy (existence of primary porosity and permeability in the sandstones). Structure is not a major controlling factor in the entrapment of natural gas, although some fracture-controlled porosity is known to occur. Porosity and permeability are best developed when the sands are reworked in the marine environment. Marine sandstones should be present in the Pennsylvania portion of Lake Erie. The sandstones are anticipated to be 20 to 30 feet thick and to have porosities of 9 to 12 percent. This is similar to what is found on the Canadian side of the lake. Toward the southeast, lower porosities are found which are generally in the 6 to 9 percent range. These are deltaic

sandstones which were deposited in a channel-dominated environment. These sandstones range from 30 to 80 feet in thickness. The shoreline appears to be the limit of commercial porosity in the Lower Silurian sandstones. Log calculations on a limited number of wells indicate that south-east of the shoreline porosities of 3 percent or less are common. Thus, the shoreline, which is also the defined boundary between the Medina Group to the northwest and the Tuscarora Formation to the southeast, also marks the limit of potential primary intergranular porosity.

REGIONAL DEPOSITIONAL FRAMEWORK

The regional depositional framework of the Lower Silurian clastics in Pennsylvania and adjacent states is illustrated in Figure 6. The map is based upon this study in northwestern Pennsylvania, Knight's work in Ohio (Knight, 1969), and Yeakel's Tuscarora outcrop work (Yeakel, 1962). Yeakel places the Lower Silurian clastic fall line, defined by pebble-size calculations, in the Chesapeake Bay region. He places the principal sediment source southeast of that area. Northwest of the fall line, sediments were deposited primarily in two accumulation centers, one in Virginia and the other in northeastern Pennsylvania. These depocenters are defined by thickness and maximum pebble size. The depocenter in northeastern Pennsylvania is represented by the Shawangunk conglomerate facies. These two accumulation centers merge to form a large detrital apron decreasing in thickness to the west-northwest. This detrital apron is represented by the Tuscarora facies of central Pennsylvania. Based upon crossbedding, maximum pebble size, facies thickness, and sand/shale ratio, combined with the regional distribution of faunas, the Tuscarora is interpreted by Yeakel to be a large alluvial plain. A continental fluvial origin for the lower part of the Tuscarora seems to best fit the observed relationships. The upper part of the Tuscarora, which is in contact with the marine Clinton shales, was probably deposited in a marginal marine environment.

The terrestrial Tuscarora facies is replaced in northwestern Pennsylvania by the transitional deltaic Medina Group. The Medina Group is primarily a complex system of small deltas. Sedimentation in the Grimsby tongue of the Medina Group occurred in channels as bar-finger deposits, distributary mouth bars, offshore bars, and longshore bars. The sandstone bodies deposited are limited in both horizontal and vertical extent. The Mississippi Delta (Fisk, 1961) is a good modern analog. Along the Lake Erie shoreline, the environment of deposition changes from transitional deltaic to marine-dominated offshore bars. Sandstone-body geometry and regional fauna distribution support this interpretation. This marine-dominated deltaic environment continues across Lake Erie into Canada.

Both the bar-dominated and channel-dominated deltaic environments in northwestern Pennsylvania provide excellent potential for the development

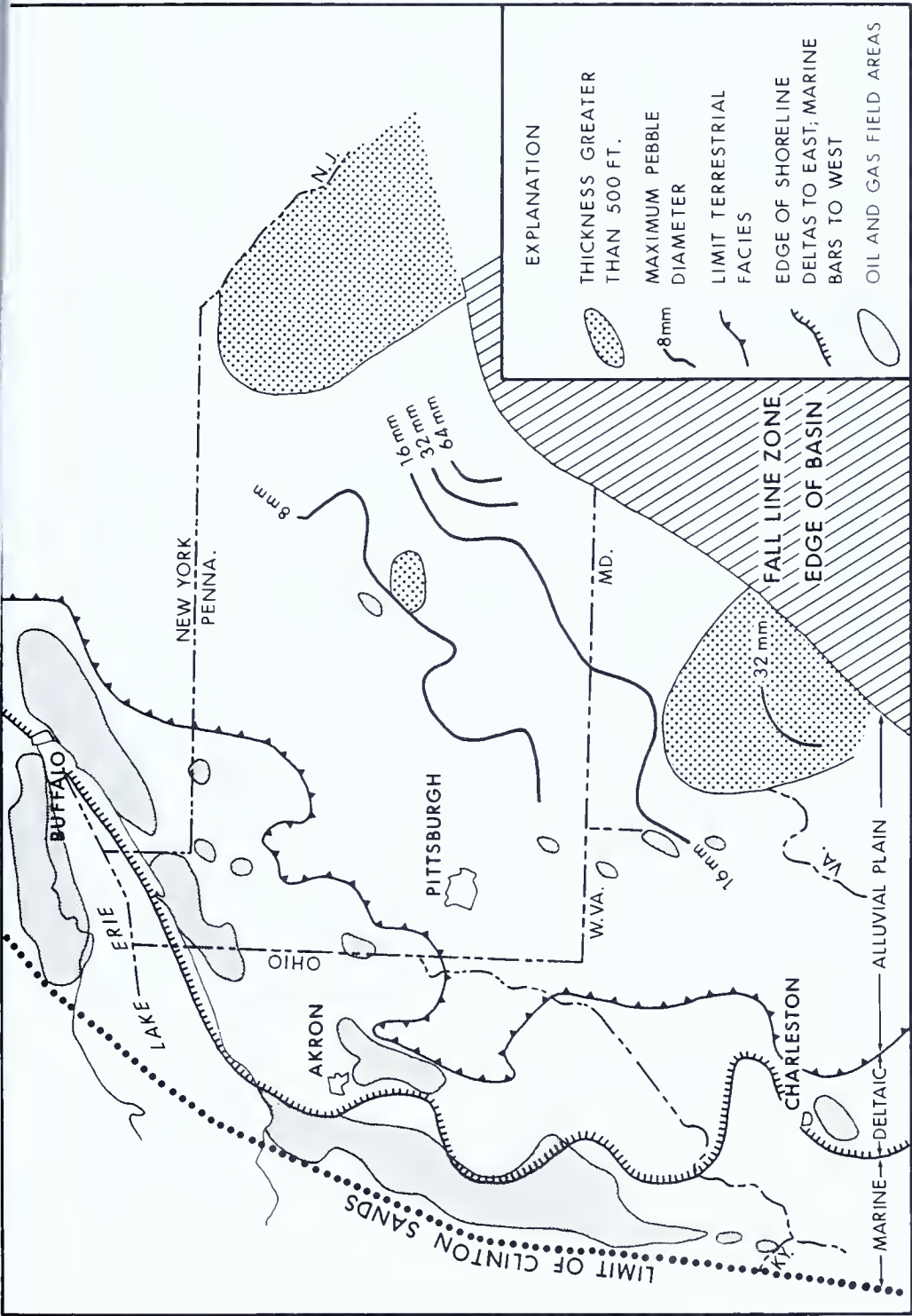


Figure 6. Medina-Tuscarora regional depositional framework in Pennsylvania and adjacent states (modified from Yeakel, 1962, and Knight, 1969).

of reservoir sandstones. Exploratory and development drilling in this area is anticipated to expand depending upon the well-head price of natural gas.

Development of the fracture-porosity traps in the Tuscarora Formation in central Pennsylvania holds great potential. These fracture-porosity traps are associated with large overthrust structures at relatively great drilling depths. The history of large volume, low Btu gas will be important factors. Drilling the Tuscarora of central Pennsylvania is a high potential, high risk exploratory venture.

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PLATE 1. NATURAL GAS PRODUCTION FROM MEDINA GROUP SANDSTONES
IN NORTHWESTERN PENNSYLVANIA

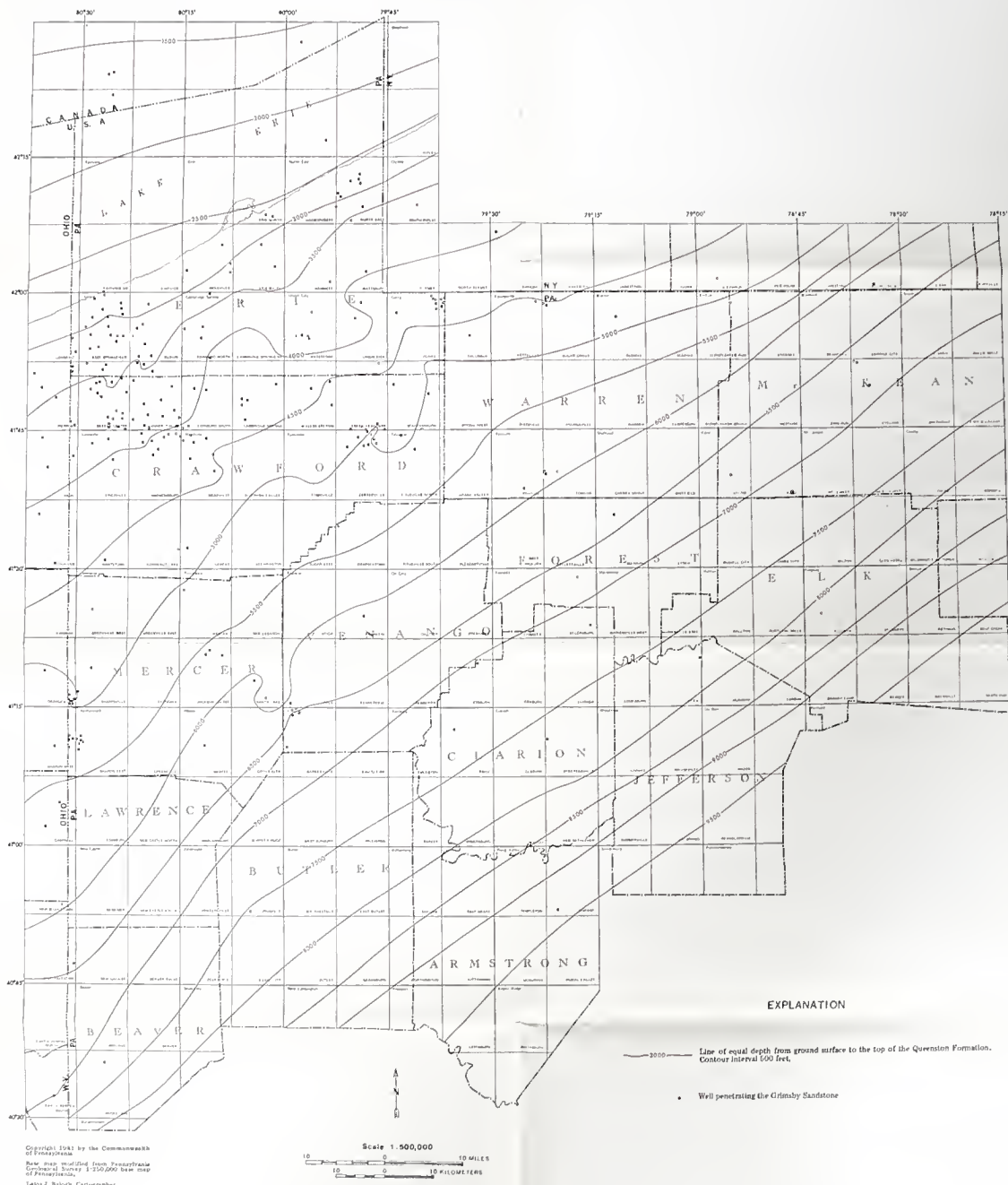
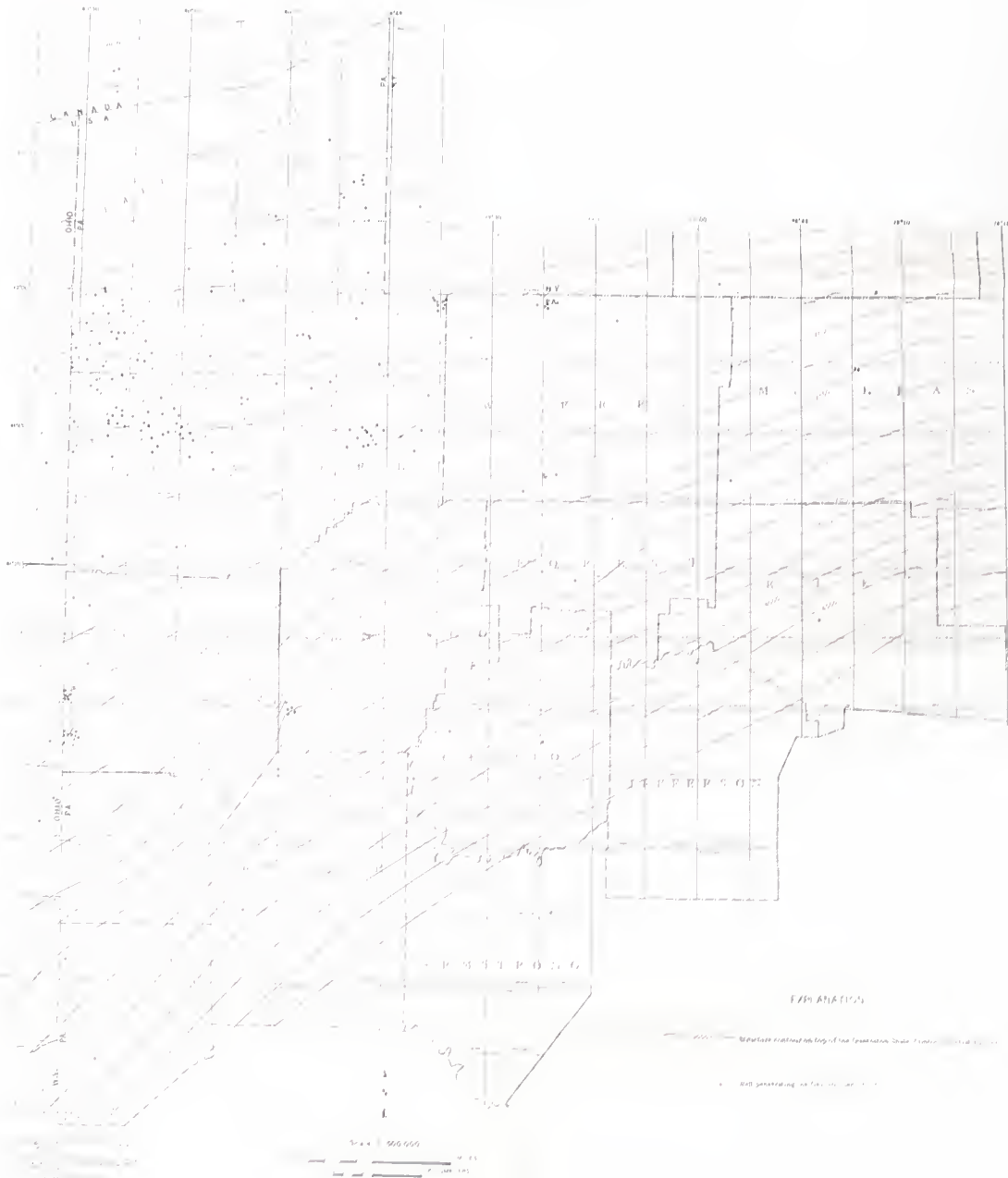


PLATE 2. DRILLING DEPTH TO THE TOP OF THE QUEENSTON SHALE
IN NORTHWESTERN PENNSYLVANIA



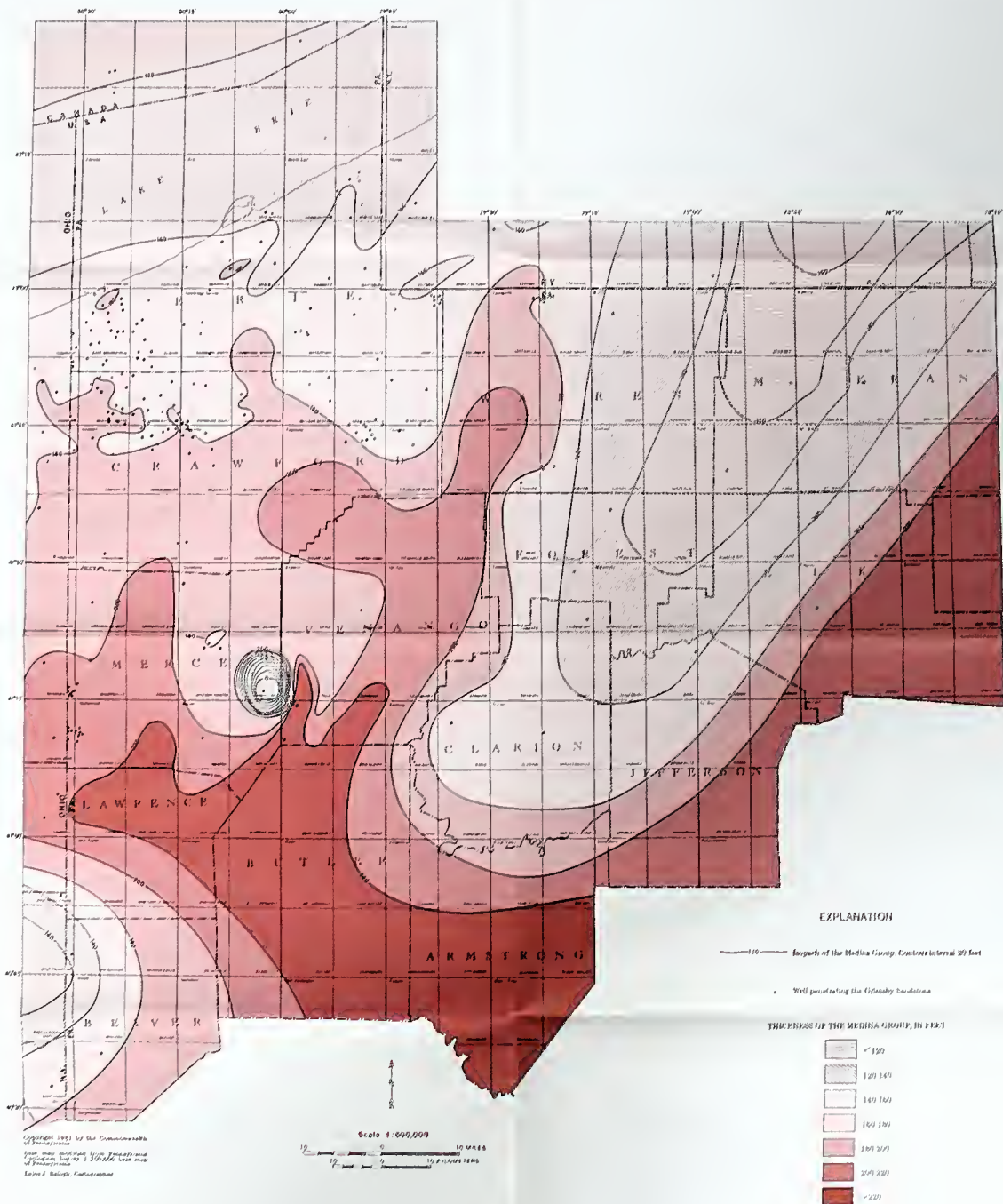


PLATE 4. ISOPACH MAP OF THE MEDINA GROUP
IN NORTHWESTERN PENNSYLVANIA

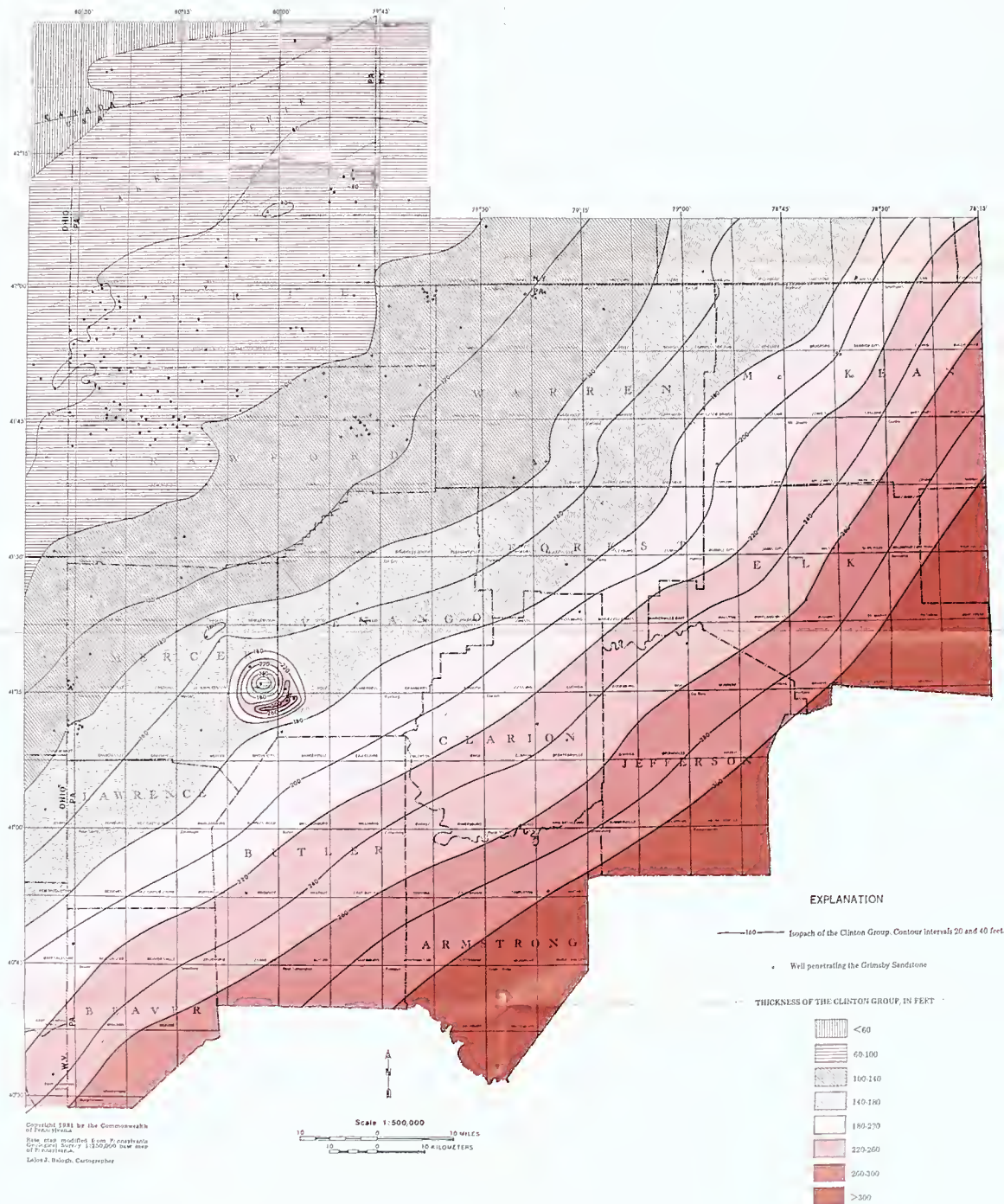


PLATE 5. ISOPACH MAP OF THE CLINTON GROUP
IN NORTHWESTERN PENNSYLVANIA

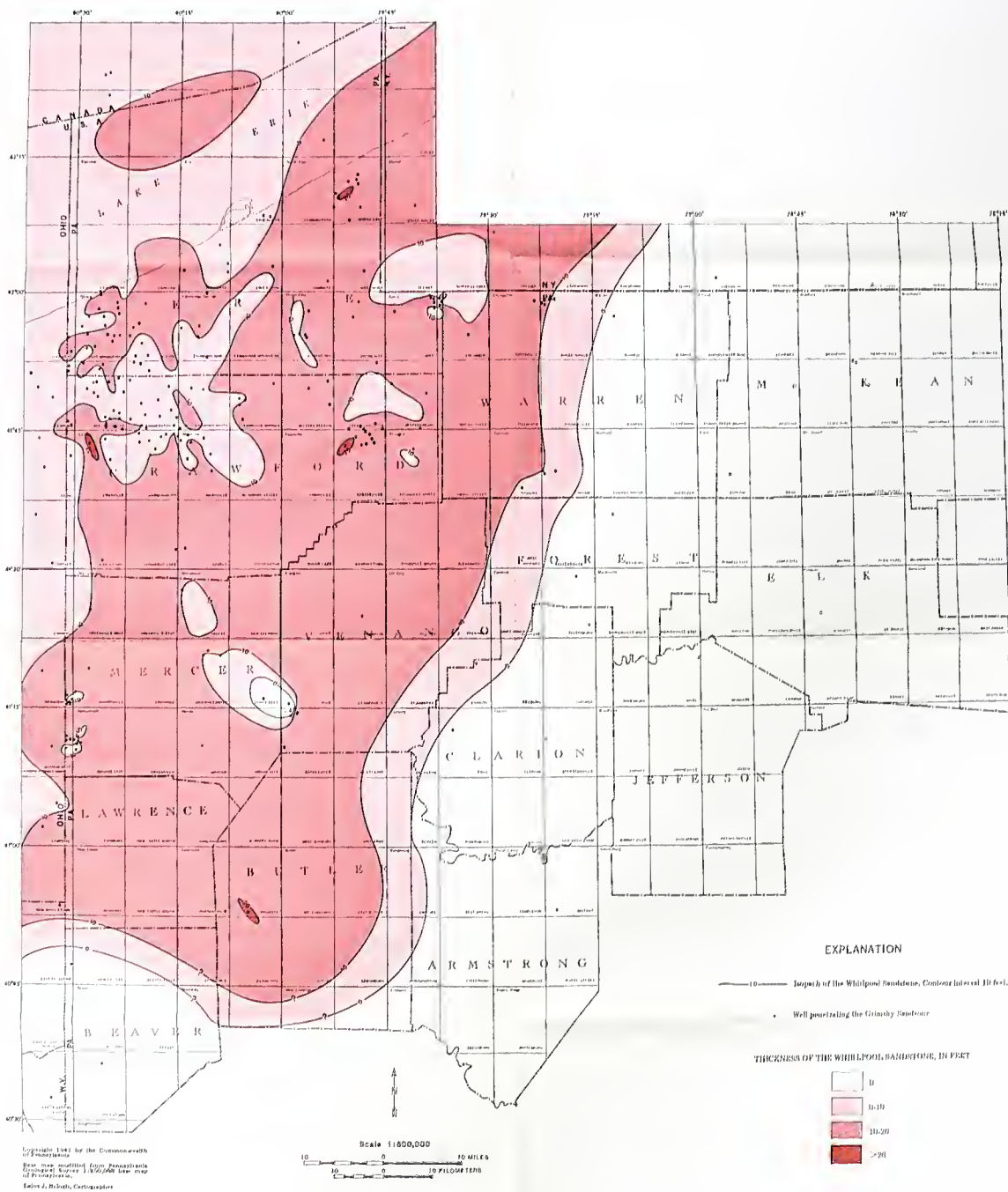


PLATE 6. ISOPACH MAP OF THE WHIRLPOOL SANDSTONE
IN NORTHWESTERN PENNSYLVANIA

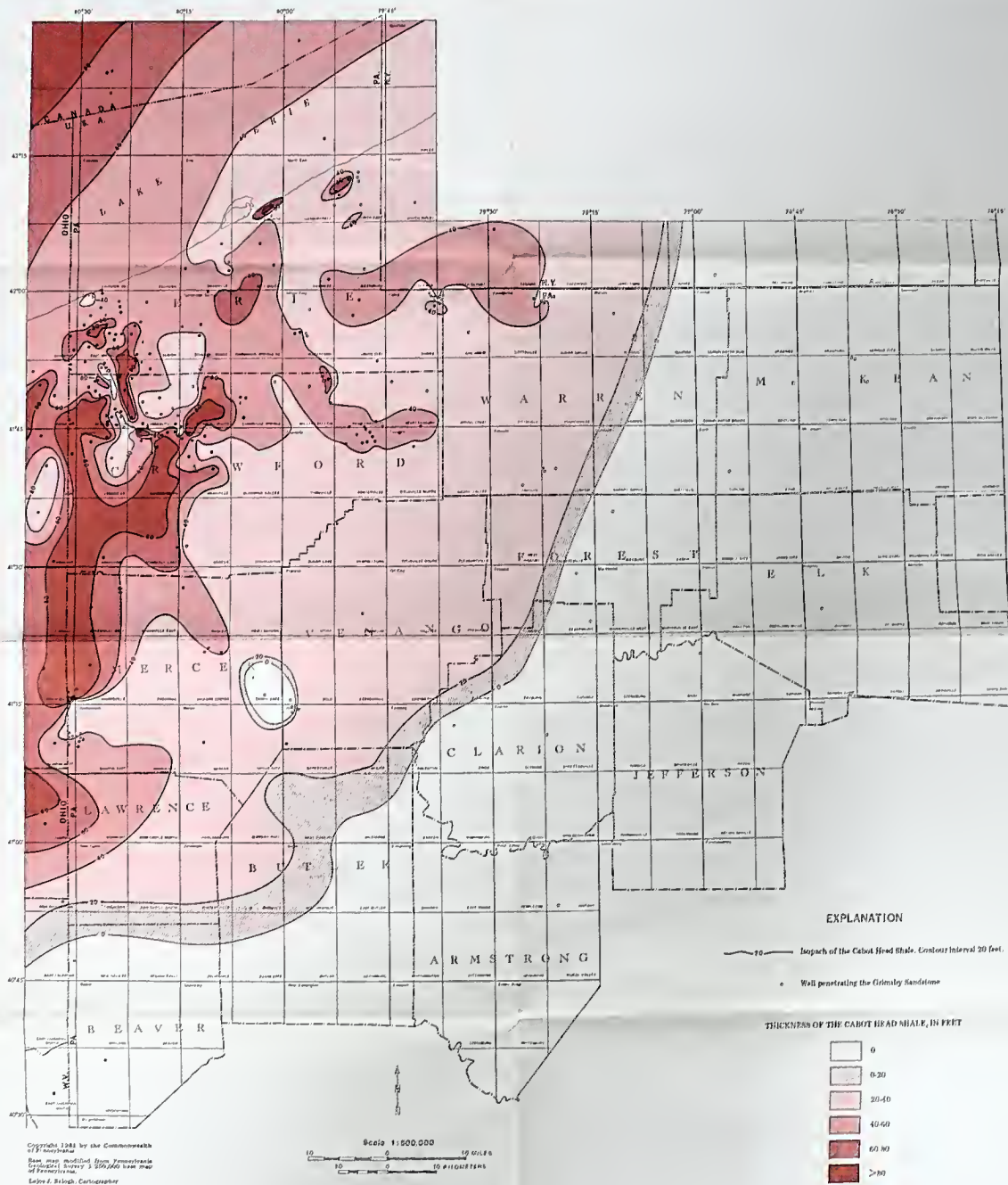


PLATE 7. ISOPACH MAP OF THE CABOT HEAD SHALE
IN NORTHWESTERN PENNSYLVANIA



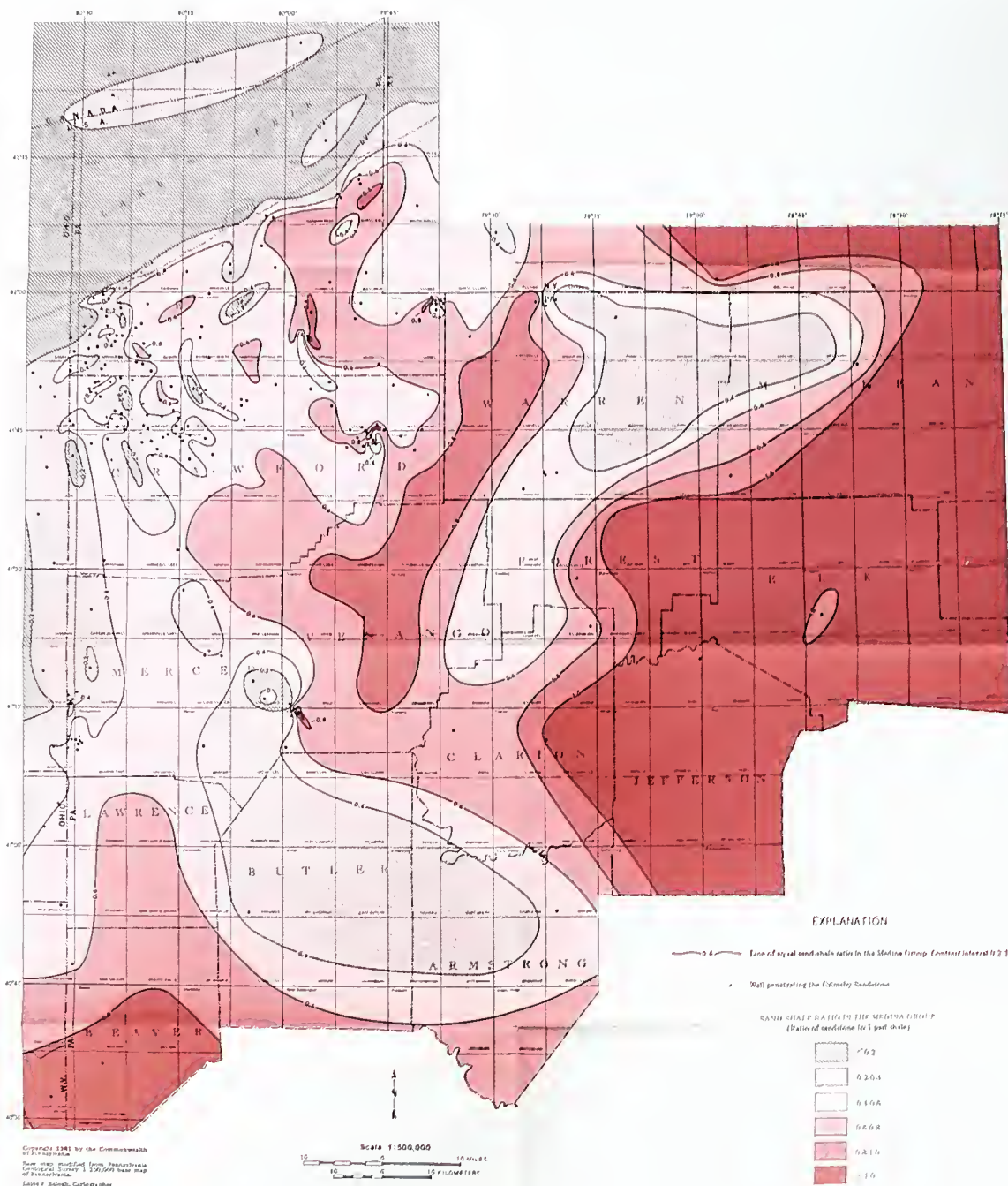


PLATE 9. SAND/SHALE RATIO IN THE MEDINA GROUP
IN NORTHWESTERN PENNSYLVANIA

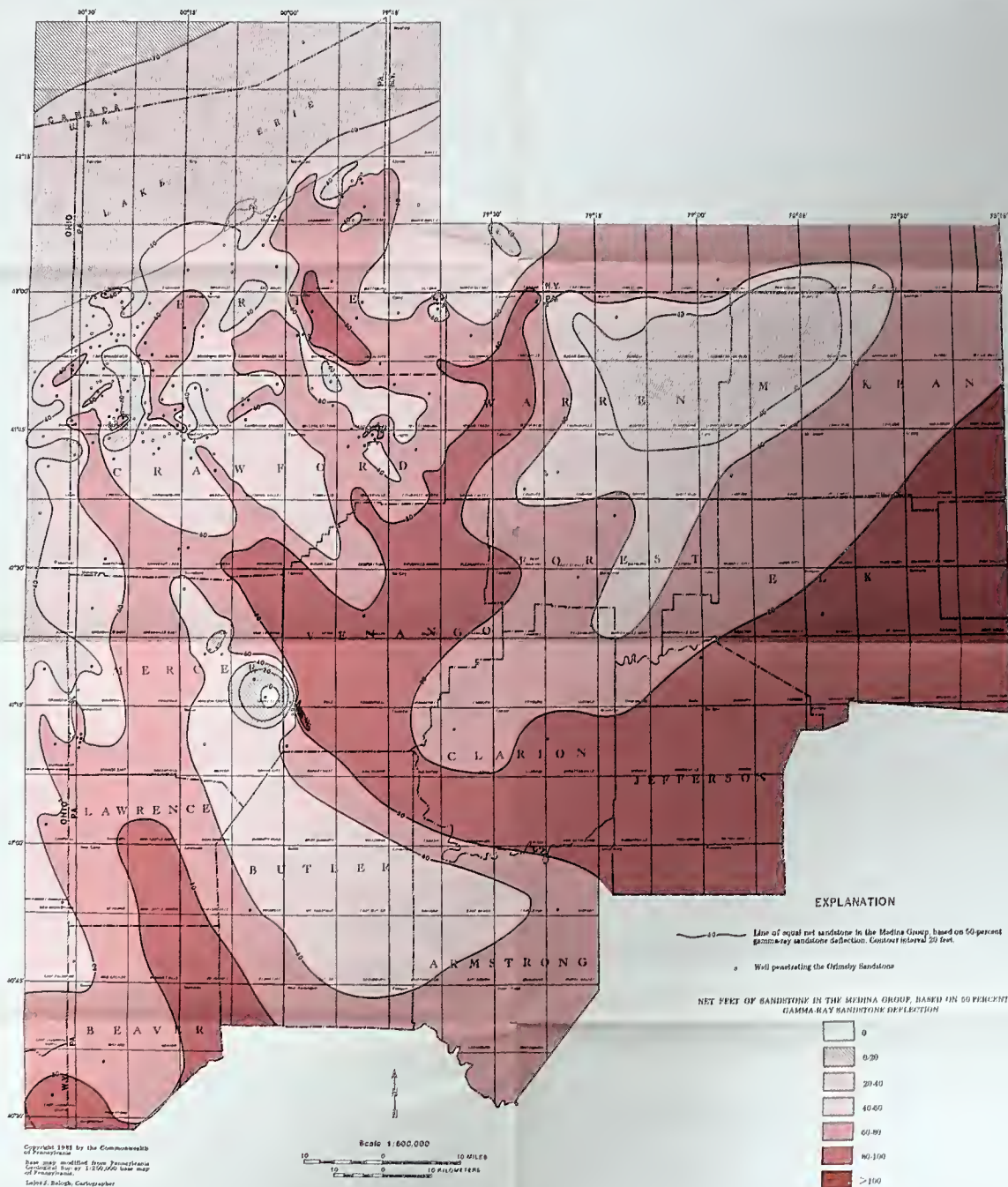


PLATE 10. NET SAND (50 PERCENT CUTOFF) IN THE MEDINA GROUP
IN NORTHWESTERN PENNSYLVANIA

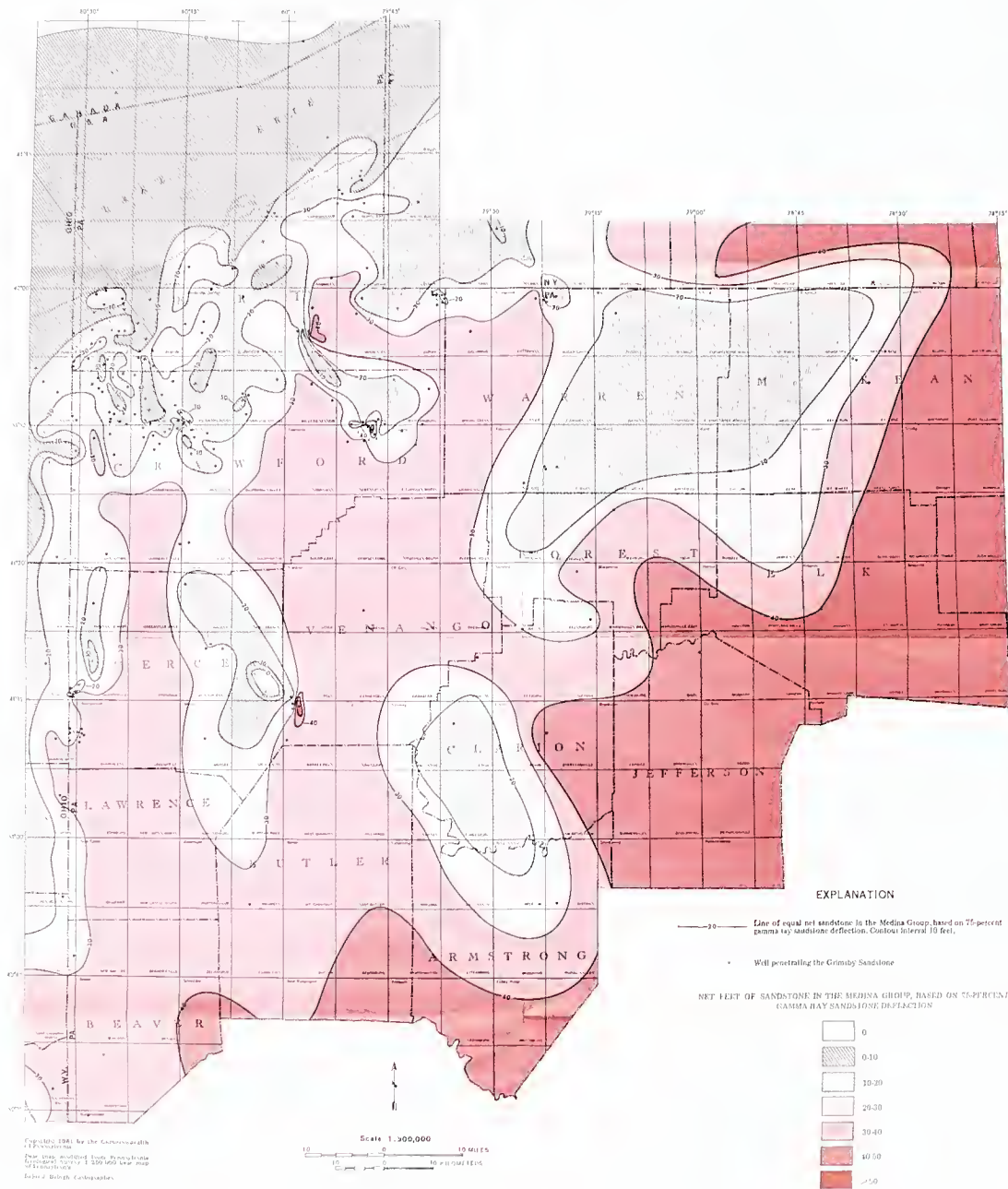


PLATE 11. NET SAND (75 PERCENT CUTOFF) IN THE MEDINA GROUP
IN NORTHWESTERN PENNSYLVANIA

